Effect of dietary supplementation of n-3 fatty acids and elevated concentrations of dietary protein on the performance of sows

R. D. Mateo,* J. A. Carroll,† Y. Hyun,‡ S. Smith,§ and S. W. Kim#[1,2]

*Department of Animal and Food Sciences, Texas Tech University, Lubbock 79409;
†USDA-ARS-Livestock Issues Research Unit, Lubbock, TX 79403; ‡Dodram B&F, Seoul, Korea 135-080;
§Department of Animal Science, Texas A&M University, College Station 77843;
and #Department of Animal Science, North Carolina State University, Raleigh 27603

ABSTRACT: A study was conducted to determine the effect of dietary supplementation of n-3 fatty acids (O3FA) with or without elevated concentrations of protein on the performance of sows during the first and the subsequent parity. Sixty-four pregnant gilts with BW of 195.0 ± 2.1 kg and backfat (BF) thickness of 12.9 ± 0.2 mm were assigned to 4 dietary treatments from d 60 of gestation (late gestation) to d 21 of lactation. Dietary treatments were 1) a control diet; 2) a high-protein diet (HP); 3) the control diet + 0.2% O3FA (O3); and 4) the HP diet + 0.2% O3FA (HPO3). For the control and O3 treatments, CP contents were 12.3% for late gestation and 17.9% for lactation, and for the HP and HPO3 treatments, CP contents were 18.4% for late gestation and 19.5% for lactation. On d 60 and 110 of gestation and after farrowing (within 12 h postfarrowing), on d 10 and 21 of lactation, BW, BF thickness, and blood samples were obtained. The total number of piglets and the number of piglets born alive and their birth weights were measured within 12 h postfarrowing. Colostrum and milk samples were obtained on d 2 and 21 of lactation, respectively. All piglets were weaned at 21 d. The wean-to-estrus interval and ADFI were recorded. The same measurements were obtained from the control and O3 groups during the subsequent parity. Dietary treatment did not affect BW, BF thickness, ADFI, and the wean-to-estrus interval of sows during their first reproductive cycle. Supplementation of O3FA increased both eicosapentaenoic acid and docosahexaenoic acid contents ($P < 0.05$) in colostrum and mature milk. First-parity litter size and piglet birth weight did not differ among treatment groups. Piglet BW was greater ($P < 0.05$) for the O3 group compared with both the control and HPO3 groups at d 10 and 21 of lactation. The same pattern was also noted for overall piglet BW gain. Both piglet and litter characteristics of the HP group did not differ from those of other groups throughout lactation. During the subsequent parity, both total and live piglet birth weights tended ($P < 0.07$) to be greater for the O3 group than for the control group. Compared with the control group, piglet BW and BW gain in the O3 group showed a pattern similar to the previous parity. Results indicated that O3FA alone during lactation improved the growth of nursing piglets, regardless of parity. However, the O3FA diet, with or without elevated protein, did not affect first-parity gestation performance, although O3FA alone may have improved piglet birth weight in the subsequent litter.

Key words: gestation, lactation, n-3 fatty acid, protein, sow

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INTRODUCTION

Nutritional strategies to improve the reproductive performance of sows commonly involve dietary manipulation. Alpha-linolenic acid and linoleic acid are members of the n-6 and n-3 (**O3FA**) family of fatty acids, respectively, and are considered essential dietary nutrients. These fatty acids are metabolically and functionally distinct and are not interchangeable (Simopoulos, 1991). Furthermore, both are also important constituents of cell membranes in various tissues (Crawford, 2000; Muskiet et al., 2004), making them critical components during rapid tissue formation (Innis, 1991; Hornstra, 2000). These fatty acids are the precursors for the synthesis of different types of eicosanoids, such as prostaglandins, thromboxanes, and leukotrienes, all of which play important roles in the regulation of both immune and reproductive functions (McCowen and

[1]Corresponding author: sungwoo_kim@ncsu.edu
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Bistrian, 2003; Muskiet et al., 2004). Although studies have been limited, dietary supplementation of fish oil in animal diets has the potential to improve the reproductive performance of sows (Rooke et al., 1998, 2000). Typical grain-based sow diets contain low amounts of O3FA, which may lead to decreased piglet survival at birth (Rooke et al., 2000) and possible overreaction of the piglet immune system (Turek et al. 1996).

The protein requirements of sows have been shown to be much greater than those suggested by the NRC (1998), especially during late gestation (Ji, 2004) because of increased nutrient needs for both fetal growth (McPherson et al., 2004) and mammary gland growth (Ji et al., 2006), and during lactation because of increased nutrient needs for milk production and mammary gland growth (Kim et al., 2005). Thus, providing appropriate protein concentrations during these periods may prevent unnecessary catabolism of body nutrient stores or the possibility of repartitioning O3FA supplemented in the diet. This study was conducted to determine the impact of dietary O3FA, with or without elevated protein concentrations, during late gestation and throughout lactation on the performance of sows and their litters during the first parity and the effects of O3FA on the subsequent parity.

MATERIALS AND METHODS

The study was approved by the Texas Tech University Animal Care and Use Committee.

Animals, Design, and Diets

The O3FA source used in the study was Gromega (JBS United, Sheridan, IN), which contained 20% O3FA in an encapsulated, protected form, with 80% ground wheat as a carrier. A total of 64 pregnant gilts (Camborough 22, Pig Improvement Co., Franklyn, KY) with an average BW of 195.0 ± 2.1 kg and a backfat (**BF**) thickness of 2.9 ± 0.2 mm were used in this study. They were housed in individual gestation crates (2.2 × 0.6 m) and checked for estrus once daily in the morning and bred twice via AI. The second AI followed the first insemination within 24 h. Semen was obtained from PIC-356 boars at the Texas Tech University Research Farm. At 60 d of gestation, pregnant gilts were grouped based on BW and randomly allotted, within BW groups, to 4 dietary treatments. The 4 dietary treatments were 1) a corn- and soybean meal-based control diet; 2) a high-protein diet (**HP**); 3) the control diet + 0.2% O3FA provided by 1% Gromega (**O3**); and 4) the HP diet + 0.2% O3FA provided by 1% Gromega (**HPO3**). All gestation diets were formulated to contain 3.1 Mcal of ME/kg. The control and O3 diets contained 12.3% CP, whereas the HP and HPO3 diets contained 18.4% CP (Table 1). The HP and HPO3 diets were formulated to contain CP concentrations and AA ratios relative to Lys, as suggested by Ji (2004) and Kim et al. (2005), by using crystalline AA. Pregnant gilts on gestation diets were fed 2 kg daily in 2 separate meals (0700 and 1800 h).

Pregnant gilts had free access to water via individual nipple drinkers throughout the entire study. Maternal BW and BF thickness were measured on d 60 and 110 of gestation. Backfat thickness was measured by ultrasound (LS-1000, Tokimec Inc., Tokyo, Japan) at the P2 position (left side of the 10th rib and 6 cm away from the spine). On d 60 and 110 of gestation, blood samples (7 mL) were collected 2 h after feeding via jugular venipuncture using heparinized tubes (Vacutainer Lithium Heparin Plus Tubes, BD, Franklin Lakes, NJ). Samples were centrifuged at 2,000 × *g* at 4°C for 15 min. Plasma was separated and transferred by transfer pipettes into 1.5-mL microcentrifuge tubes (National Scientific, San Rafael, CA) and stored at −20°C until further analysis. At 110 d of gestation, all pregnant gilts were transferred to individual farrowing crates (1.5 × 2.2 m). Total and live piglets born per litter, as well as individual birth weights of piglets, and the BW and BF thickness of sows were measured within 24 h postfarrowing.

When sows with a litter size of less than 7 were excluded, the remaining 49 first-parity sows (197.7 ± 2.5 kg of BW and 14.87 ± 0.21 mm of BF) were fed the experimental diets based on their original assignment during the 21-d lactation period. The numbers of sows excluded because of small litter size were 1, 4, 4, and 6 for the control, HP, O3, and HPO3 group, respectively. Within treatment groups, litter size was equalized to a minimum of 10 by cross-fostering when needed within 24 h postfarrowing. During lactation, all diets contained 3.2 Mcal of ME/kg. The control and O3 diets contained 17.9% CP, whereas the HP and HPO3 diets contained 19.5% CP (Table 2). The HP and HPO3diets were formulated to contain CP concentrations and AA ratios relative to Lys, as suggested by Ji (2004) and Kim et al. (2005), by using crystalline AA. Lactating sows had free access to feed and water during the entire lactation period. Water was provided via individual nipple drinkers accessible to the sow and the litter. The amount of feed consumed was measured daily.

The farrowing room temperature was maintained at 25°C, with supplemental heat for piglets provided by portable heat lamps. Piglets were not provided with creep feed or milk replacer during the entire 21-d lactation period. Body weight and BF thickness of sows, as well as individual piglet BW, were measured at d 10 and 21 of lactation. Blood samples from sows were obtained at d 10 and 21 of lactation. Procedures for collecting, handling, and processing blood samples were identical to those completed during the gestation period. On d 2 and 20 of lactation, milk samples were collected. To collect milk samples, piglets were temporarily separated from the sow, the udder was cleaned with a warm towel, and a single dose of oxytocin (20 US Pharmacopeia units, Phoenix Pharmaceuticals Inc.

Table 1. Composition of gestation diets (as-fed basis)

	Gestation diet[1]			
Item	Control	O3	HP	HPO3
Ingredient, %				
Corn	73.70	72.90	58.72	57.92
Soybean meal, 44% CP	11.00	11.00	25.70	25.70
Alfalfa meal, 17% CP	5.00	5.00	5.00	5.00
Molasses cane	5.00	5.00	5.00	5.00
Lipid[2]	0.50	0.30	0.50	0.30
Gromega[3]	—	1.00	—	1.00
L-Arg	—	—	0.021	0.021
L-Lys·HCl	—	—	0.215	0.215
L-Thr	—	—	0.161	0.161
Potassium chloride	0.25	0.25	0.25	0.25
Sodium chloride	0.35	0.35	0.35	0.35
Vitamin-mineral mix[4]	1.50	1.50	1.50	1.50
Dicalcium phosphate	2.20	2.20	2.05	2.05
Limestone	0.50	0.50	0.53	0.53
Total	100.00	100.00	100.00	100.00
Chemical composition				
DM, %	89.1	89.1	89.2	89.2
ME, kcal/kg	3,100	3,100	3,100	3,100
CP, %	12.3	12.3	18.4	18.4
Ca, %	0.94	0.94	0.94	0.94
Available P, %	0.47	0.47	0.47	0.47
Total P, %	0.69	0.69	0.72	0.72
Digestible Lys, %	0.51	0.50	1.07	1.07
Digestible Thr, %	0.39	0.39	0.76	0.76
Digestible Trp, %	0.11	0.11	0.20	0.19
Digestible Arg, %	0.62	0.62	1.05	1.05
Digestible Val, %	0.49	0.48	0.71	0.71

[1]Gestation diets were provided at 2 kg daily in 2 separate meals (0700 and 1800 h). Control = corn- and soybean meal-based control diet; O3 = control diet supplemented with 0.2% n-3 fatty acids (O3FA) provided by 1% Gromega (JBS United, Sheridan, IN) at the expense of 0.2% oil and 0.8% corn; HP = high-protein diet that contained CP concentrations and AA ratios relative to Lys, as suggested by Ji (2004) and Kim et al. (2005), by using crystalline AA (Ajinomoto Co. Inc. Tokyo, Japan); HPO3 = HP diet supplemented with 0.2% O3FA provided by 1% Gromega (JBS United) at the expense of 0.2% oil and 0.8% corn.

[2]A mixture of animal fat and restaurant grease.

[3]Gromega = a marine source of O3FA supplied by JBS United.

[4]The vitamin premix provided the following per kilogram of complete diet: 46.7 mg of manganese as manganous oxide; 75 mg of iron as $FeSO_4$; 103.8 mg of zinc as ZnO; 9.5 mg of copper as copper sulfate; 0.72 mg of iodide as ethylenediamine dihydroiodide; 0.23 mg of selenium as Na_2SeO_3; 7,556 IU of vitamin A as vitamin A acetate; 825 IU of vitamin D_3; 61.9 IU of vitamin E; 4.4 IU of vitamin K as menadione sodium bisulfate; 54.9 μg of vitamin B_{12}; 13.7 mg of riboflavin; 43.9 mg of D-pantothenic acid as calcium pantothenate; 54.9 mg of niacin; and 1,650 mg of choline as choline chloride.

St. Joseph, MO) was administered intramuscularly to facilitate milk secretion. Samples (12 to 15 mL) were collected manually from all functional teats into 15-mL polypropylene conical tubes and were stored at −20°C until further analysis. All piglets were weaned at 21 d, after which sows were returned to gestation stalls. Wean-to-estrus interval was recorded.

All sows that returned to heat were bred according to the procedures used during the first parity. Sows in the control and O3 groups were identified and fed their original gestation diets beginning at d 60 of gestation to determine the effects of O3FA supplementation on second-parity sow performance. One sow in the O3 group was not successfully bred and was removed. Twenty-five sows were used during the second parity (214.3 ± 2.9 kg of BW and 13.67 ± 0.17 mm of BF). Variables measured, sampling, and all other management procedures during the second parity were identical to those completed during the first parity.

Chemical Analyses

All chemicals were obtained from Sigma Chemical Company (St. Louis, MO). Plasma samples were analyzed for urea concentrations by using a colorimetric method involving reaction with phenol and hypochlorite as described previously by Wu and Knabe (1994). Colostrum and milk were analyzed for fat content by using the Babcock method (AOAC, 1995), for protein (N × 6.38) by using an automated N analyzer (Leco FP-2000, Leco Corp., St. Joseph, MI), and for total milk solids (AOAC, 1995). Fatty acid composition in

Table 2. Composition of lactation diets (as-fed basis)

	Lactation diet[1]			
Item	Control	O3	HP	HPO3
Ingredient, %				
Corn	66.75	65.95	62.28	61.48
Soybean meal, 44% CP	26.00	26.00	30.00	30.00
Lipid[2]	1.30	1.10	1.20	1.00
Gromega[3]	—	1.00	—	1.00
L-Val	—	—	0.20	0.20
L-Lys·HCl	—	—	0.30	0.30
L-Thr	—	—	0.12	0.12
Potassium chloride	0.25	0.25	0.25	0.25
Sodium chloride	0.35	0.35	0.35	0.35
Vitamin-mineral mix[4]	3.00	3.00	3.00	3.00
Dicalcium phosphate	1.55	1.55	1.50	1.50
Limestone	0.80	0.80	0.80	0.80
Total	100.00	100.00	100.00	100.00
Chemical composition				
DM, %	90.0	90.0	90.1	90.1
ME, kcal/kg	3,200	3,200	3,200	3,200
CP, %	17.9	17.9	19.5	19.5
Ca, %	0.80	0.80	0.80	0.80
Available P, %	0.37	0.37	0.37	0.37
Total P, %	0.63	0.63	0.64	0.64
Digestible Lys,%	0.91	0.91	1.25	1.25
Digestible Thr, %	0.61	0.61	0.78	0.78
Digestible Trp, %	0.20	0.20	0.22	0.22
Digestible Arg, %	1.04	1.04	1.15	1.15
Digestible Val, %	0.72	0.72	0.98	0.97

[1]Lactation diets were fed ad libitum throughout the lactation period. Control = corn- and soybean meal-based control diet; O3 = control diet supplemented with 0.2% n-3 fatty acids (O3FA) provided by 1% Gromega (JBS United, Sheridan, IN) at the expense of 0.2% oil and 0.8% corn; HP = high-protein diet that contained CP concentrations and AA ratios relative to lysine, as suggested by Ji (2004) and Kim et al. (2005), by using crystalline AA; HPO3 = HP diet supplemented with 0.2% O3FA provided by 1% Gromega (JBS United) at the expense of 0.2% oil and 0.8% corn.

[2]A mixture of animal fat and restaurant grease.

[3]Gromega = a marine source of O3FA supplied by JBS United.

[4]The vitamin premix provided the following per kilogram of complete diet: 46.7 mg of manganese as manganous oxide; 75 mg of iron as $FeSO_4$; 103.8 mg of zinc as ZnO; 9.5 mg of copper as copper sulfate; 0.72 mg of iodide as ethylenediamine dihydroiodide; 0.23 mg of selenium as Na_2SeO_3; 7,556 IU of vitamin A as vitamin A acetate; 825 IU of vitamin D_3; 61.9 IU of vitamin E; 4.4 IU of vitamin K as menadione sodium bisulfate; 54.9 μg of vitamin B_{12}; 13.7 mg of riboflavin; 43.9 mg of D-pantothenic acid as calcium pantothenate; 54.9 mg of niacin; and 1,650 mg of choline as choline chloride.

the colostrum and milk was analyzed by gas chromatography as described by Smith et al. (2002).

Statistical Analysis

Data were analyzed using the MIXED procedure (SAS Inst., Inc., Cary, NC) following a randomized complete block design. Sow was considered as the experimental unit. Data for the number of piglets born dead were analyzed by using the Friedman test as described by SAS. For second-parity piglet and litter performance data, initial piglet BW and litter weight, respectively, were included as covariates. Separation of means was done by using the PDIFF option of SAS. Probability values less than 0.05 were considered significant; values less than 0.10 were indicative of a trend; and values equal to or greater than 0.10 were considered nonsignificant.

RESULTS

Gestation Performance

Performance of pregnant gilts during the first parity is presented in Table 3. Maternal BW and BF thickness did not differ among treatments on d 60 and 110 of gestation (Table 3). No significant differences were noted among treatments with respect to the total number of piglets born, piglets born alive, or piglets born dead (Table 3). Similarly, piglet birth weights, whether based on the number born live or the total number born, did not differ among treatment groups. Further, variation in birth weights within a litter, based on either total number born or number born alive, also showed no difference among treatment groups (Table 3).

Performance of pregnant sows during the second parity is shown in Table 4. Maternal BW and BF thickness

Table 3. Gestation performance of pregnant gilts fed n-3 fatty acids (O3FA) or a high-protein diet, individually or in combination, during late gestation

	Treatment[1]					
Item	Control	O3	HP	HPO3	SEM	*P*-value
n	13	18	15	18		
BW at 60 d, kg	195.7	197.1	195.3	195.7	2.1	0.473
BW at d 110, kg	218.3	221.9	221.0	224.8	2.0	0.321
Backfat thickness at d 60,[2] mm	12.7	12.7	13.3	13.1	0.2	0.418
Backfat thickness at d 110,[2] mm	14.8	15.1	15.7	15.4	0.2	0.242
Total born, n	11.14	11.74	11.25	11.66	0.27	0.806
Total born alive, n	10.39	11.14	10.29	10.48	0.26	0.618
Avg. birth wt,[3] kg	1.54	1.56	1.56	1.47	0.02	0.504
Avg. litter birth wt,[4] kg	15.59	16.89	15.93	15.02	0.42	0.410
Born dead,[5] n	0.77	0.61	1.06	1.22	—	0.580
Within litter birth wt variation,[6] kg	0.215	0.242	0.245	0.256	0.010	0.595

[1]Gestation diets were fed at 2 kg/d in 2 separate meals (0700 and 1800 h). Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 0.2% O3FA (Gromega, JBS United, Sheridan, IN); HP = group fed the high-protein diet; HPO3 = group fed the HP diet supplemented with 0.2% O3FA (Gromega, JBS United).

[2]Backfat thickness was measured at the P2 position (left side of the 10th rib and 6 cm away from the spine).

[3]Average piglet birth weight based on total number of piglets born alive.

[4]Average litter birth weight based on total number of piglets born alive.

[5]Data analyzed by using the Friedman test (SAS Inst., Inc., Cary, NC).

[6]SD of piglet birth weight per litter based on total piglets born alive.

did not differ between the control and O3 groups on d 60 and 110 of gestation (Table 4). No differences in total piglets born, piglets born alive, and piglets born dead were noted among treatment groups. However, piglet birth weight based on both total piglets born (1.54 vs. 1.65 kg; $P < 0.06$) and piglets born alive (1.55 vs. 1.67 kg; $P < 0.07$) tended to be greater in piglets of sows fed the O3 diets compared with those of sows fed the control diet. In contrast, litter weight based on either total piglets born or piglets born alive did not differ among treatments. Variation in birth weights within a litter, based on either total piglets born or piglets born alive showed no difference among treatment groups.

Lactation Performance

Lactation performance of first-parity sows is presented in Table 5. Neither BW nor BF thickness differed among treatment groups immediately after farrowing, at d 10 and 21 of lactation. The ADFI and

Table 4. Gestation performance of second-parity sows fed diets supplemented with n-3 fatty acids (O3FA) or without O3FA

	Treatment[1]			
Item	Control	O3	SEM	*P*-value
n	12	13		
BW at 60 d, kg	214.5	214.0	2.9	0.868
BW at d 110, kg	241.5	243.2	2.8	0.650
Backfat thickness at d 60,[2] mm	13.8	13.5	0.2	0.314
Backfat thickness at d 110,[2] mm	15.8	16.1	0.2	0.480
Total born, n	11.2	11.1	0.3	0.943
Total born alive, n	10.8	10.8	0.3	0.991
Avg. birth wt,[3] kg	1.55	1.67	0.03	0.065
Avg. litter birth wt,[4] kg	16.66	17.86	0.46	0.159
Born dead,[5] n	0.58	0.42	—	0.609
Within litter birth wt variation,[6] kg	0.277	0.239	0.014	0.198

[1]Gestation diets were fed at 2 kg/d in 2 separate meals (0700 and 1800 h). Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 0.2% O3FA (Gromega, JBS United, Sheridan, IN).

[2]Backfat thickness was measured at the P2 position (left side of the 10th rib and 6 cm away from the spine).

[3]Average piglet birth weight based on total number of piglets born alive.

[4]Average litter birth weight based on total number of piglets born alive.

[5]Data analyzed using the Friedman test (SAS Inst. Inc., Cary, NC).

[6]SD of piglet birth weight per litter based on total piglets born alive.

Table 5. Lactation performance of first-parity sows fed n-3 fatty acids (O3FA) or a high-protein diet, individually or in combination, during late gestation and throughout lactation

	Treatment[1]					
Item	Control	O3	HP	HPO3	SEM	*P*-value
n	12	14	11	12		
Sow BW loss, kg	14.2	13.5	14.0	10.4	1.9	0.861
Sow BF loss, mm	2.8	3.2	3.0	3.0	0.3	0.969
Sow ADFI, kg	5.7	5.5	5.9	5.7	0.1	0.560
Return to estrus, d	4.8	4.6	4.8	4.7	0.1	0.863
Litter size after cross-fostering, n	11.3	11.1	11.0	11.3	0.4	0.181
Litter mortality, %	8.4	10.9	7.4	8.1	2.6	0.751
Piglet BW, kg						
0 d	1.45	1.51	1.57	1.44	0.03	0.241
10 d	3.04^{a}	3.50^{b}	3.37^{ab}	3.17^{a}	0.07	0.046
21 d	5.20^{a}	6.09^{b}	5.69^{ab}	5.31^{a}	0.11	0.011
Piglet BW gain, kg						
0 to 10 d	1.60	1.96	1.81	1.73	0.05	0.111
10 to 21 d	2.17	2.58	2.30	2.16	0.07	0.083
Overall	3.76^{a}	4.54^{b}	4.12^{ab}	3.91^{a}	0.10	0.026
Litter wt, kg						
0 d	16.67	18.40	17.37	16.58	0.32	0.125
10 d	32.90^{a}	38.12^{b}	35.62^{ab}	32.93^{a}	0.73	0.018
21 d	54.04^{a}	64.46^{b}	59.12^{ab}	55.22^{a}	1.23	0.004
Litter wt gain, kg						
0 to 10 d	16.3	19.7	18.2	16.3	0.59	0.089
10 to 21 d	21.3	26.3	23.5	22.6	0.75	0.063
Overall	37.4^{a}	46.0^{b}	41.6^{ab}	39.0^{a}	1.12	0.017

^{a,b}Within a row, means lacking a common superscript letter differ ($P < 0.05$).

[1]Lactation diets were fed ad libitum. Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 0.2% O3FA (Gromega, JBS United, Sheridan, IN); HP = group fed the high-protein diet; HPO3 = group fed the HP diet supplemented with 0.2% O3FA (Gromega, JBS United).

wean-to-estrus interval did not differ among treatment groups. Litter mortality did not differ among treatment groups. Initial piglet BW did not differ among treatment groups. At d 10 of lactation, BW of piglets from sows fed the O3 diets were greater (3.50 kg; $P < 0.05$) than those of both the control (3.04 kg) and HPO3 (3.17 kg) groups. However, piglet BW between the O3 and HP groups did not differ, nor did piglet BW differ between the HP group and all other treatment groups. A similar pattern was observed at d 21 of lactation, wherein piglets from the O3 group had greater (6.09 kg; $P < 0.05$) BW compared with those in the control (5.20 kg) and HPO3 (5.69 kg) groups (Table 5).

Piglet BW gain from d 0 to 10 of lactation did not differ among treatment groups. Piglet BW gain from d 10 to 21 of lactation tended ($P < 0.09$) to be greater for the O3 group compared with both the control and HPO3 groups. Overall (d 0 to 21 of lactation) piglet BW gain was greater ($P < 0.05$) for the O3 group compared with the control and HPO3 groups, but no differences were observed between the O3 and HP groups (Table 5). Piglet BW gain for the HP group also did not differ from those of the other treatment groups. Litter weight at d 0 of lactation did not differ among treatment groups. The O3 group had a greater ($P < 0.05$) litter weight compared with the control and HPO3 groups at d 10 of lactation, but no difference was noted between the O3 and HP groups. Litter weight of the HP group also did not differ from those of the other treatment groups. On d 21 of lactation, litter weight was greater ($P < 0.05$) in the O3 group compared with the control and HPO3 groups, but no difference was noted between the HP and O3 groups. Litter weight gain both during d 0 to 10 of lactation ($P < 0.09$) and during d 10 to 21 ($P < 0.07$) of lactation tended to be greater for the O3 group compared with the control and HPO3 groups. Litter weight gain during d 0 to 21 of lactation was greater ($P < 0.05$) for the O3 (46.0 kg) group compared with both the control (37.4 kg) and HPO3 (39.0 kg) groups, but no difference was noted between the O3 and HP groups. Litter weight gain of the HP group also did not differ from those of the other treatment groups.

Lactation performance of sows during the second parity fed either the control or O3 diet is presented in Table 6. The BW and BF thickness of sows immediately after farrowing, at d 10, and at d 21 of lactation did not differ among treatment groups. The ADFI among treatment groups did not differ. Litter mortality also did not differ among treatment groups.

Results showed differences in piglet BW between the O3 and control groups at d 0 (after cross-fostering) of the second lactation, with the O3 group (1.65 vs. 1.54 kg; $P < 0.05$) having greater BW compared with the

Table 6. Lactation performance of second-parity sows fed diets supplemented with n-3 fatty acids (O3FA) or without O3FA

	Treatment[1]			
Item	Control	O3	SEM	*P*-value
n	12	13		
Sow BW loss, kg	10.1	11.2	2.2	0.809
Sow BF loss, mm	2.5	2.8	0.1	0.260
Sow ADFI, kg	6.5	6.3	0.1	0.207
Litter size after cross-fostering, n	10.8	10.8	0.3	0.859
Litter mortality, %	5.8	4.4	2.1	0.652
Piglet BW, kg				
0 d	1.54[a]	1.65[b]	0.02	0.035
10 d	3.42	3.26	0.11	0.412
21 d	5.49	6.01	0.18	0.059
Piglet BW gain, kg				
0 to 10 d	1.82	1.70	0.10	0.413
10 to 21 d	2.06[a]	2.72[b]	0.12	0.002
Overall	3.89[a]	4.41[b]	0.17	0.059
Litter wt, kg				
0 d	17.02[a]	17.98[b]	0.40	0.049
10 d	35.08	33.92	1.11	0.595
21 d	56.31	62.30	1.93	0.079
Litter wt gain, kg				
0 to 10 d	17.60	16.43	1.01	0.594
10 to 21 d	21.25[a]	28.21[b]	1.30	0.003
Overall	38.83	44.82	1.78	0.079

[a,b]Within a row, means lacking a common superscript letter differ ($P < 0.05$).

[1]Lactation diets were fed ad libitum. Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 2% O3FA (Gromega, JBS United, Sheridan, IN).

control group; therefore, piglet BW at d 0 of lactation was included as a covariate for analyzing piglet performance data. Results showed no differences among treatment groups in piglet BW at d 10. However, the O3 group tended to have greater (6.01 vs. 5.49 kg; $P < 0.06$) BW compared with the control group at d 21 of lactation. No differences in piglet BW gain from d 0 to 10 of lactation were noted among treatment groups. However, piglet BW gain from d 10 to 21 of lactation was greater for the O3 group (2.72 vs. 2.06 kg; $P < 0.01$) compared with the control group. Overall (d 0 to 21 of lactation) piglet BW gain tended to be greater (4.4 vs. 3.9 kg; $P < 0.06$) for the O3 group compared with the control group.

Litter weight was greater for the O3 group (17.98 vs. 17.02 kg; $P < 0.05$) compared with the control group at d 0 of lactation; therefore, litter weight at d 0 of lactation was included as a covariate for analyzing litter performance data. Results showed no differences in litter weight among treatment groups at d 10 of lactation. However, on d 21 of lactation, litter weight tended to be greater (62.30 vs. 56.31 kg; $P < 0.08$) for the O3 group compared with the control group. Litter weight gain from d 0 to 10 of lactation did not differ among treatment groups. However, litter weight gain from d 10 to 21 of lactation was greater (28.21 vs. 21.25 kg; $P < 0.01$) for the O3 group compared with the control group. Overall (d 0 to 21 of lactation) litter weight gain tended to be greater (44.82 vs. 38.83 kg; $P < 0.08$) for the O3 group compared with the control group.

Milk Composition and Colostral IgG Concentration

Milk fat, total solids, and protein content of both colostrum (2 d) and mature milk (20 d) did not differ among treatment groups (Table 7). Colostral (2 d of lactation) IgG concentrations were greater ($P < 0.01$) in sows fed the O3 and HPO3 diets compared with those fed the control and HP diets (Table 7).

Plasma Urea Concentrations

Initial plasma urea concentrations at 60 d of gestation did not differ among treatment groups (Table 7). However, plasma urea concentrations were greater for both the HP (4.1 nmol/L) and HPO3 (4.4 nmol/L) groups compared with the control (3.2 nmol/L) and O3 (3.2 nmol/L) groups at d 110 of gestation. Values between the control and O3 groups and between the HP and HPO3 groups did not differ. The same pattern was noted on d 10 and 21 of lactation (Table 7).

Colostral and Milk Fatty Acid Composition

Results showed an increase ($P < 0.01$) in DHA and EPA concentrations of both colostrum and mature milk from sows fed diets supplemented with O3FA (O3 and HPO3) compared with those without (Table 8). However, α-linolenic acid concentrations were less ($P < 0.01$) in both colostrum and mature milk from sows fed diets

Table 7. Colostral and milk composition, urea, and colostral IgG concentrations of first-parity sows fed n-3 fatty acids (O3FA) or high-protein diets, individually or in combination, during late gestation and throughout lactation

	Treatment[1]					
Item	Control	O3	HP	HPO3	SEM	*P*-value
Colostrum (d 2 of lactation)						
Protein, %	6.6	6.9	7.0	7.1	0.241	0.574
Fat, %	8.4	8.7	8.3	8.4	0.081	0.300
Total solids, %	22.2	20.6	21.1	20.4	0.735	0.426
IgG, mg/mL	19.9[a]	24.4[b]	18.6[a]	29.5[b]	1.130	<0.001
Milk (d 17 of lactation)						
Protein, %	5.8	5.7	5.8	6.0	0.130	0.279
Fat, %	7.1	7.2	7.0	7.1	0.170	0.902
Total solids, %	19.3	18.8	18.1	18.7	0.670	0.685
Plasma urea, mmol/L						
60 d of gestation	2.7	2.5	2.5	2.6	0.157	0.742
110 d of gestation	3.2[a]	3.2[a]	4.1[b]	4.4[b]	0.074	<0.001
10 d of lactation	4.1[a]	4.1[a]	4.8[b]	4.8[b]	0.092	<0.001
21 d of lactation	4.5[a]	4.3[a]	4.8[b]	4.9[b]	0.079	<0.001

[a,b]Within a row, means lacking a common superscript letter differ ($P < 0.01$).

[1]Gestation diets were fed at 2 kg/d in 2 separate meals (0700 and 1800 h); lactation diets were provided ad libitum. Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 2% O3FA (Gromega, JBS United, Sheridan, IN); HP = group fed a high-protein diet; HPO3 = group fed the HP diet supplemented with 2% O3FA (Gromega, JBS United).

supplemented with O3FA compared with those without O3FA supplementation (Table 8). No differences in n-6 fatty acids in both colostrum and mature milk were noted among treatment groups (Table 8).

DISCUSSION

First-Parity Performance

Results from the present study showed that O3FA supplementation alone to first-parity sows during lactation improved piglet growth, but O3FA supplemented with high protein (HP and HPO3) or without high protein (control and O3) to pregnant gilts did not affect gestation performance. Although previous studies have shown improvements in litter size (Webel et al., 2003; Spencer et al., 2004), these studies supplemented O3FA at least 30 d before breeding, whereas the current study began supplementation on d 60 of gestation. Because litter size is determined at a much earlier stage of gestation and the majority of conceptus loss occurs during the peri-implantation period (Pope, 1994), dietary supplementation of O3FA beginning at d 60 of gestation was not expected to increase litter size at birth in this study. Similar results have been obtained with multiparous sows when using fish oil supplemented during similar gestation stages (Rooke et al., 2001a,b), further suggesting that O3FA supplementation during late ges-

Table 8. Colostral (2-d) and milk (20-d) fatty acid composition of first-parity sows fed n-3 fatty acids (O3FA) or a high-protein diet, individually or in combination, during late gestation and throughout lactation

	Treatment[1]											
	2 d of lactation						20 d of lactation					
Item	Control	O3	HP	HPO3	SEM	*P*-value	Control	O3	HP	HPO3	SEM	*P*-value
n	12	14	11	12			12	14	11	12		
n-6 fatty acids[2]												
18:2n-6	14.05	15.77	14.94	15.62	0.72	0.772	11.88	11.55	11.76	11.27	0.38	0.674
20:4n-6 + 22:0	0.95	0.99	0.90	0.99	0.04	0.403	0.54	0.48	0.56	0.52	0.02	0.267
O3FA[2]												
18:3n-3	0.58[a]	0.19[b]	0.52[a]	0.12[b]	0.05	<0.001	0.29[a]	0.09[b]	0.55[a]	0.08[b]	0.05	<0.001
20:5n-3	0.03[a]	0.15[b]	0.05[a]	0.15[b]	0.01	<0.001	0.02[a]	0.16[b]	0.02[a]	0.14[b]	0.01	<0.001
22:6n-3	0.03[a]	0.30[b]	0.07[a]	0.23[b]	0.01	<0.001	0.05[a]	0.22[b]	0.02[a]	0.19[b]	0.01	<0.001

[a,b]Within a row, means lacking a common superscript letter differ ($P < 0.001$).

[1]Gestation diets were fed at 2 kg/d; lactation diets were fed ad libitum. Control = group fed a corn- and soybean meal-based control diet; O3 = group fed the control diet supplemented with 0.2% O3FA (Gromega, JBS United, Sheridan, IN); HP = group fed the high-protein diet; HPO3 = group fed the HP diet supplemented with 0.2% O3FA (Gromega, JBS United).

[2]Values are in percentage of total fatty acids; 18:2n-6, linoleic acid; 20:4n-6 + 20:0, arachidonic acid (ArA) + behenic acid; 18:3n3, α-linolenic acid (ALA); 20:5n-3, eicosapentaenoic acid (EPA); 22:6n-3, docosahexaenoic acid (DHA).

tation does not seem to affect litter birth size, regardless of parity. In the current study, pregnant gilts were also fed high-protein diets (HP and HPO3) from d 60 of gestation, wherein protein concentration was increased from 12.3 to 18.4% as suggested by Ji (2004). However, the high-protein diets did not improve the gestation performance of gilts, but rather increased plasma urea concentrations, indicating that the concentrations of protein used in these diets were in excess (Cooper et al., 2001).

Results of the study showed improvements in the growth of piglets from first-parity sows in the O3 group compared with sows in both the control and HPO3 groups. Rooke et al. (2001a) reported that fish oil supplementation during either late gestation or lactation resulted in heavier piglets at all stages of lactation compared with sows fed the control diet throughout the study. The authors suggested that the increase in growth was due to improved piglet status (i.e., brain fatty acid composition; Rooke et al., 2001b) and vigor at birth (Rooke et al., 2001a,b). Because O3FA are important brain lipid components (Sastry, 1985; Muskiet et al., 2004), it is likely that these fatty acids have significant effects on brain development and function (Crawford, 2000), and thus behavior. Consistent with this notion, previous reports have shown that O3FA supplementation improves learning behavior in pigs (Ng and Innis, 2003) as well as in rodents (Ikemoto et al., 2001), which may involve both dopamine (Delion et al., 1994; Zimmer et al., 2000) and serotonin metabolism (Owens and Innis, 1998), both of which have been implicated in a variety of neural functions, including feeding behavior (McEntee and Crook, 1991). This may also explain in part reports showing a decreased latency to suckle in pigs (Rooke et al., 2001a) as well as in lambs (Capper et al., 2006), which is vital because newborn piglets have a low fat content, limited glycogen stores, and an immature immune system (Boyd et al., 1978; Drew and Owen, 1988). However, further investigation is required to confirm positive behavioral responses of piglets to maternal O3FA supplementation.

It was reported previously that dietary fat supplementation may result in changes in milk fat content, thereby increasing milk energy content (Pettigrew, 1981) and possibly piglet growth rate. As expected, no differences in fat content of both colostral (d-2) and mature (d-20) milk from O3FA supplementation were noted in the present study when lipid contents were matched among treatment diets, suggesting that the improvement in growth may not have been due to an increase in milk energy content. Although lactose was not measured directly, total solids in both colostral and mature milk, including protein content, did not differ among treatments; therefore, lactose content would not be expected to vary. However, increases in docosahexaenoic acid (**DHA**) and eicosapentaenoic acid (**EPA**) were noted in both colostrum and mature milk from sows fed diets supplemented with O3FA (O3 and HPO3) compared with those fed diets without O3FA supplementation (control and HP), which is consistent with previous reports in sows (Arbuckle and Innis, 1993; Taugbol et al., 1993; Rooke et al., 1998) as well as in humans (Harris et al., 1984; Jensen et al., 2000). Although, α-linolenic acid concentrations were greater in both colostrum and mature milk from sows fed diets without O3FA supplementation, its conversion to longer chain PUFA such as DHA is not efficient (Muskiet et al., 2004). These results suggest that compared with providing neonates with α-linolenic acid, providing them with preformed long-chain PUFA such as DHA and EPA is more effective in improving neonatal growth.

The potential immunological effects of O3FA (Calder et al., 2002) in piglets through milk consumption may play a role in the noted improvement in piglet growth, possibly by repartitioning nutrients away from the immune system and toward growth (Korver and Klasing, 1997; Carroll et al., 2003). In addition, consistent with previous reports in rodents (Prickett et al., 1982), colostral IgG concentration, which is positively correlated with piglet IgG synthesis (Rooke and Bland, 2002), was greater in sows fed lactating diets supplemented with O3FA compared with those fed the control and HP diets.

It is not clear why the growth response of piglets from sows fed the HPO3 diet did not perform as well as those from sows fed the O3 diet. Reports have suggested that increased energy, but not protein, intake during late gestation may have adverse effects on mammary gland growth in gilts (Weldon et al., 1991), and therefore neonatal growth, because mammary gland growth is directly associated with milk production. However, this is unlikely the case in the present study because all diets were formulated to be isocaloric. Alternatively, studies in rats have shown that the effect of protein on insulin release by the neonate may involve the type of fatty acid in the diet during gestation (Maloney et al., 2007). In addition, Marin et al. (1995) showed that the maternal dietary protein content is capable of regulating the lipid composition of fetal membranes, and therefore eicosanoid release, which plays an important role in both animal health and growth (Dunlop et al., 1984; Calder et al., 2002). However, these results were obtained by using low-protein maternal diets. Nevertheless, these results indicate that both PUFA and the amount of protein in maternal diets during gestation can interact to affect the development of the offspring (Bouziane et al., 1994; Maloney et al., 2007). Although the mechanisms are unclear, this interaction may have resulted in reduced, but not adverse, growth in piglets from sows fed the HPO3 diet compared with the O3 diet.

Results from the present study showed no differences in growth between piglets from sows fed diets containing an elevated protein concentration compared with those from sows fed diets containing a conventional protein concentration, suggesting that the protein concentrations in the latter diets were sufficient and that increases beyond this concentration were in excess of

the amount required to support neonatal growth. These results are supported by the increased plasma urea concentrations during all stages of lactation. In addition, no differences were noted in milk protein composition and BW and BF losses among treatments in the present study, suggesting that the extra protein was not used for either these purposes. It is worth mentioning that milk production and piglet growth may not be altered easily (Mahan, 1979; Greenhalgh et al., 1980), especially at the protein concentrations used in the current study (Jones and Stahly, 1999b), because sows are capable of mobilizing tissue reserves to support normal neonatal growth (Kim et al., 2001; Clowes et al., 2005). Studies have shown that the litter growth rate can be sustained even when feed intake and protein intake are restricted by as much as 50% (Pluske et al., 1998). Further, earlier reports (Jones and Stahly, 1999b) showed that improvements in litter weight at weaning from increasing the lactation diet protein concentration were observed when dietary protein was less than 17%, but beyond this concentration, the protein concentration did not result in further improvements. This is in agreement with the results of the present study, wherein protein concentrations were near 18% for the diets not high in protein. In contrast, Ji (2004) fed sows high-protein diets containing AA ratios similar to those used in the present study, which resulted in improved litter weight gain. Further studies are required to determine possible explanations for the differences observed between the results of the current study and those of Ji (2004).

As previously indicated, no differences in BW, BF thickness, and ADFI were observed in sows fed diets supplemented with O3FA or with elevated protein concentrations, either individually or in combination. These results are consistent with previous reports in which fish oil was used as an O3FA source (Rooke et al., 2000, 2001a,b,c). Results from a study by Jones and Stahly (1999a) comparing 2 concentrations of protein on lactation performance showed that sows fed low-protein diets lost more BW on a daily basis compared with sows fed high-protein diets. However, in that study a very wide range of protein concentrations was used (8.7 vs. 20.7%) as compared with the present study, which used 17.9% CP for the control and O3 groups and 19.5% CP for the HP and HPO3 groups. In contrast, Ji (2004) reported that feeding protein concentrations similar to those used in the current study during lactation resulted in less BW loss during the 21-d lactation period. Further, that study, which used AA ratios relative to Lys similar to those in the present study, showed that the sows fed diets with these ratios lost less BF compared with the control group, regardless of the dietary protein concentration. However, data from these results were averaged from sows in their first, second, and third parities. When only first-parity sows were assessed, no differences in BW and BF loss, as well as ADFI, were noted among treatments.

Second-Parity Performance

Results from the present study showed that supplementing second-parity sows with O3FA alone may improve piglet birth weight. During lactation, supplementation of second-parity sows with O3FA alone improved piglet growth. Previous research using the same O3FA source as that used in the current study showed increases in subsequent litter size (total piglets born and piglets born alive) when sows were supplemented from late gestation up to the rebreeding period (Webel et al., 2003, 2004). In contrast, Rooke et al. (2000) failed to demonstrate any improvements in litter size at birth from sows fed fish oil from postbreeding up to farrowing. Similar results were noted in the present study, wherein O3FA supplementation was done from 60 d of gestation up to weaning at 21 d and was continued again beginning at 60 d of the following gestation period for the subsequent parity. These results suggest that benefits from O3FA supplementation may be realized when supplementation includes the period up to rebreeding, possibly via increased early embryo survival (Webel et al., 2004), as previously shown in lactating cows (Mattos et al., 2005; Ambrose et al., 2006). Although no increase in subsequent litter size was noted from the O3FA-supplemented group, both subsequent piglet birth weight based on either total piglets or piglets born alive tended to be greater compared with the control group. Previous reports suggest that increased birth weight from O3FA supplementation may result from increased fetal growth (Olsen et al., 1990), possibly via an eicosanoid-induced increase in blood flow (Rogers et al., 2004) or gestation length (Olsen et al., 1986, 1992; Rooke et al., 2001b). However, gestation length (115 $\pm$ 0.4 d), regardless of parity, did not respond to O3FA supplementation in the current study. Rooke et al. (2001b) reported decreased piglet birth weights from multiparous sows fed diets supplemented with fish oil beginning at 58 d of gestation. However, sows were induced to farrow in that study, thereby resulting in decreased birth weights (Rooke et al., 2001a). Fatty acid composition of the O3FA source has also been suggested as a factor in piglet birth weight. For example, using salmon oil (Rooke et al., 2001b) resulted in decreased birth weights, whereas using tuna oil (Rooke et al., 1998, 2000) did not, probably because salmon oil contains a high EPA-to-DHA ratio (Rooke et al., 2001c). Eicosapentaenoic acid is known to inhibit arachidonic acid synthesis (Rooke et al., 2001c; McCowen and Bistrian, 2003), the status of which has been correlated with birth weight (Carlson et al., 1992, 1993). These results further suggest a need to determine optimal ratios between these fatty acid families. The discrepancy between first-parity and subsequent parity birth weights may have been due, at least in part, to the growth pattern of sows during these 2 periods. It is generally known that first-parity gilts are young and therefore still growing (Averette et al., 1999); thus, sup-

plementation of O3FA may have been used for growth and not for pathways that may have brought about possible improvements in birth weight. Consistent with first-parity lactation performance, the growth of nursing piglets was also improved by maternal O3FA supplementation during the second parity. Possible reasons for improvements have been discussed earlier.

In summary, results indicated that O3FA alone during lactation improved the growth of nursing piglets, regardless of parity. However, O3FA supplementation, with or without elevated protein concentrations, did not affect first-parity gestation performance, although O3FA alone might improve subsequent piglet birth weight.

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